**Cooling of neutron stars and hybrid stars with a stiff hadronic EoS**

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**Abstract**

Within the "nuclear medium cooling" scenario of neutron stars all reliably known temperature - age data, including those of the central compact objects in the supernova remnants of Cassiopeia A and XMMU-J1732, can be comfortably explained by a set of cooling curves obtained by variation of the star mass within the range of typical observed masses. The recent measurements of the high masses of the pulsars PSR J1614-2230 and PSR J0348-0432 on the one hand, and of the low masses for PSR J0737-3039B and the companion of PSR J1756-2251 on the other, provide independent proof for the existence of neutron stars with masses in a broad range from $\sim 1.2$ to $2\ M_\odot$. The values $M > 2\ M_\odot$ call for sufficiently stiff equations of state for neutron star matter. We investigate the response of the set of neutron star cooling curves to a stiffening of the nuclear equation of state so that maximum masses of about $2.4\ M_\odot$ would be accessible and to a deconfinement phase transition from such stiff nuclear matter in the outer core to colour superconducting quark matter in the inner core. Without a readjustment of cooling inputs the mass range required to cover all cooling data for the stiff DD2 equation of state should include masses of $2.426\ M_\odot$ for describing the fast cooling of CasA while the existence of a quark matter core accelerates the cooling so that CasA cooling data are described with a hybrid star of mass $1.674\ M_\odot$.

# 1 Introduction

The cooling of compact stars (CS) is an observable phenomenon which is governed by the interplay of structure and composition (viz. the equation of state (EoS)) of CS with the transport properties and neutrino emissivities

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of the matter they are made of. It therefore allows, in principle, to explore the otherwise inaccessible physics of neutron star interiors. Until recently the complex situation with many poorly known parameters in the theory of CS cooling allowed for many possible scenarios due to the fact that the observational data on masses and radii as well as temperature and age of CS were not sufficiently constraining.

Now the situation has tremendously improved with the observation of the segment of a cooling curve for the central compact object in the remnant of the historical supernova Cassiopeia A [1, 2], thus with known age, temperature and rate of cooling followed over the past 13 years since its discovery [3, 4, 5]. In principle, the observed spectra and distance allow even for a rough constraint on mass and radius of the cooling CS [3, 6]. These data require a fast cooling process in the CS interior which becomes apparent in the photon luminosity at the surface of the star after 300 yr. On the other hand, the CS cooling model must also explain that XMMU J173203.3-344518 [7], another compact object in a supernova remnant, being hotter and older than CasA, at an age between 10 and 40 kyr. The solution of the puzzle might be connected with a strong medium dependence of cooling inputs, as provided by the density dependent medium modifications of the nucleon-nucleon interaction caused by the softening of the pion degree of freedom with the density, and by the density dependent superfluid pairing gaps, see [8] for details. The key idea that the cooling of various sources should be essentially different due to the difference in their masses was formulated long ago [9], when still there existed the opinion that all masses of neutron stars should be approximately fixed closely to the value 1.4 $M_\odot$. The recent measurements of the masses of the pulsars PSR J1614-2230 [10], PSR J0348-0432 [11] and J00737-3039B [12] and of the companion of PSR J1756-2251 [13] provide the proof for the existence of CS with masses varied in a broad range, at least from $\sim 1.2$ to 2 $M_\odot$.

First, influence of in-medium effects based on assumption [9] on the neutron star cooling was demonstrated in [14] within various exploited EoS. The "nuclear medium cooling" scenario subsequently developed in [15, 16] provides a successful description of all known cooling data for neutron stars with low magnetic fields. Recently, it has even been improved [17] in order to comply with the constraint that the EoS used for calculating the CS sequence should reach a maximum mass in the range $M = 2.01 \pm 0.04\ M_\odot$ as measured for PSR J0348+0432 [11], see also [10]. The most efficient processes within the nuclear medium cooling scenario are the medium modified Urca (MMU) process, e.g. $nn \to npe\bar{\nu}$, and the pair-breaking-formation processes (PBF).

The latter processes, $N \to N_{\rm pair}\nu\bar{\nu}$, $N = n$ or $p$, are enhanced owing to their one-nucleon nature [18, 19], despite they are allowed only in the presence of the nucleon pairing. The direct Urca reaction, $n \to npe\bar{\nu}$, is forbidden at least for $M < 1.5\ M_\odot$ (so called "strong" DU constraint), see [20].

Still, the EoS used in [17] might be not sufficiently constrained. A future measurement of radii of CS might require stiffer hadronic EoS, which would entail a restructuring of the star and modification of its cooling characteristics. Recent radius determinations from timing residuals suggest the larger radii and thus stiffer hadronic EoS [21]. Moreover, for stiffer hadronic EoS, a deconfinement transition in the CS interior is not excluded [22, 23, 24]. Also, more massive objects than those have been carefully measured in [10, 11] are not excluded. For example there are some although indirect indications [25] that the mass of the black-widow pulsar PSR J1311-3430 may even reach $M = 2.7\ M_\odot$. Incorporating systematic light-curve differences the authors estimated that the mass should be at least $M > 2.1\ M_\odot$.

Therefore, in the present contribution we shall explore these actual EoS aspects. Here we compute the cooling curves within our nuclear medium cooling scenario exploiting the stiff DD2 EoS [26]. Additionally, as an alternative to the purely hadron scenario, we incorporate a possibility of the deconfinement phase transition from such stiff EoS of the nuclear matter in the outer core to colour superconducting quark matter in the inner core.

## 2 Stiff hadronic EoS and high-mass hybrids

The baseline EoS for our previous work was the APR based fit formula provided by Heiselberg and Hjorth-Jensen [27]

$$E_N = un_0 \left[ m_N + e_{\rm B} u \frac{2+\delta-u}{1+\delta u} + a_{\rm sym} u^{0.6} (1-2x_p)^2 \right] , \tag{1}$$

where $u = n/n_0$, with $n_0 = 0.16\ {\rm fm}^{-3}$ the nuclear saturation density, $e_{\rm B} \simeq -15.8$ MeV is the nuclear binding energy per nucleon, $a_{\rm sym} \simeq 32$ MeV is the symmetry energy coefficient and we chose $\delta = 0.2$. We have recently improved this EoS by invoking an excluded volume for nucleons related to their quark substructure and the Pauli blocking between nucleons due to quark exchange forces. This was accomplished by the replacement

$$u \longrightarrow u \left[ 1 - n_0 v_0 {\rm e}^{-(\beta/u)^\sigma} \right]^{-1} , \tag{2}$$

where $v_0 = 0.125$ fm$^3$ stands for the effective excluded volume, $\beta = 6$ and $\sigma = 4$ [17].

The sequence of CS resulting from integrating the Tolman–Oppenheimer–Volkoff equation is shown in the left panel of Fig. 1, denoted as "HDD" and it serves as the reference point for the present study. The black dot on that curve at the mass 1.498 $M_\odot$ (for the pairing gaps computed following model I, see [17]) denotes the star configuration which would describe the cooling curve that fits best the CasA cooling data.

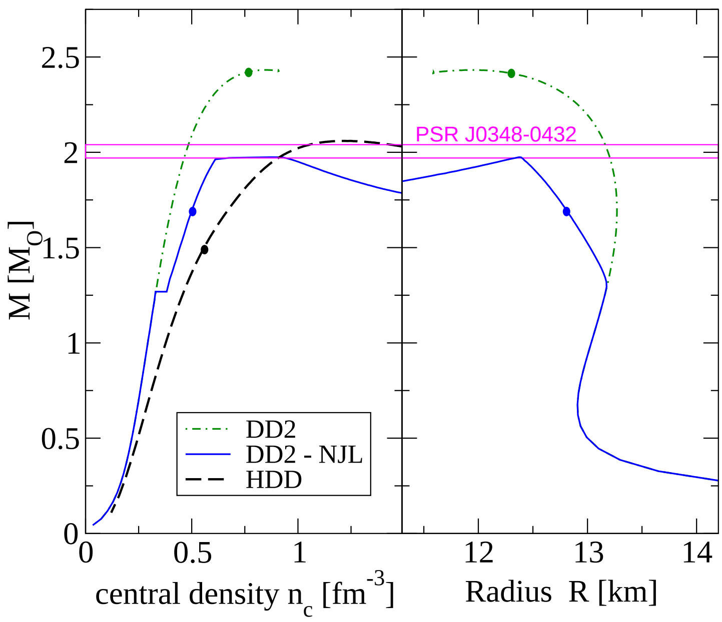


Figure 1: Mass vs. central baryon density (left) and vs. radius (right) for the stiff DD2 hadronic EoS (dash-dotted lines) and for the hybrid EoS with a deconfinement transition to superconducting NJL quark matter (solid lines). For comparison, the softer hadronic EoS model HDD [17] is shown in the left panel (dashed line). All three EoS fulfil the constraint for the maximum mass of 1.97 $M_\odot$. The dots indicate the configurations for which the cooling curve would describe the observational data from CasA.

There are indications from a recent radius determination for the nearest millisecond pulsar PSR J0437-4715 [21] that a stiffer EoS is required to sup-

port (at $2\sigma$ confidence) radii $\geq 13$ km in the mass segment between 1.5 and 1.8 $M_\odot$. The density dependent relativistic mean-field EoS of Ref. [28] with the well calibrated DD2 parametrization [26] meets such requirements, see the dash-dotted line in the right panel of Fig. 1. It fulfills all standard constraints for symmetric nuclear matter around saturation density and from nuclear structure. It has a density dependent symmetry energy in perfect agreement with the recent constraint by Danielewicz and Lee [29] and with ab-initio calculations for pure neutron matter [30]. The DU threshold is not reached within the DD2 EoS that is also a good feature, since all the stars with the density in the center above the DU threshold value cool down so rapidly that become invisible in the soft $X$ rays. Note however that due to the stiffness of this EoS, it does not fulfil the Danielewicz "flow constraint" [31] for densities above $2n_0$. This is the price we pay for a possibility to substantially increase the maximum neutron star mass and the radii of CS.

This DD2 EoS will be used by us as a benchmark for a stiff hadronic EoS. It is plain from inspecting the left panel of Fig. 1 that stiffening the EoS does not only entail larger CS radii but at the same time lower densities of the neutron star interior. As a consequence, a slower cooling than for stars of the HDD sequence is expected at the same mass. In other words, in order to cover the same set of cooling data with a stiffer EoS the range of masses attributed to the set of cooling curves shall be shifted to higher values.

A sufficiently stiff hadronic EoS like DD2 paves the way for exploring scenarios with phase transitions to exotic forms of matter in the CS interior like hyperons [32] and/or quark matter, see Refs. [22, 23, 24] for recent examples which despite a softening due to the phase transition meet the constraint of the 2 $M_\odot$ pulsar mass measurement [11], see the solid lines in Fig. 1. In those examples the quark matter EoS is described by a colour superconducting two-flavor NJL model in the 2SC phase with a stiffening due to a vector mean field. We shall now discuss the results for CS cooling obtained with these EoS.

# 3 Cooling model of CS

Since we would like to isolate the effects of changing just the EoS on the cooling behaviour, we adopt here all cooling inputs such as the neutrino emissivities, specific heat, crust properties, etc., from our earlier works performed on the basis of the HHJ EoS [16] and HDD EoS [17] for the hadronic matter. The pairing gaps will be taken following the model II. Of key im-

portance is that we will use here the very same density dependence of the effective pion gap $\widetilde{\omega}(n)$ as in our other previous works, e.g., see Fig. 1 of [17]. To be specific we assume the pion condensation to appear for $n > 3n_0$ thus exploiting the curves 1a+2+3.

The heat conductivity is treated in the same simplified way as in [16]. There, we used an additional suppressing pre-factor $\zeta_\kappa$ to show the qualitative effect. With the gaps from the model II, the best description of the CasA data was achieved with the mass $M \geq 1.73\ M_\odot$ at the parameter $\zeta_\kappa \leq 0.015$. Since our aim here is just to demonstrate the qualitative effect of a stiffening of the EoS on the cooling we will follow the same simplified procedure.

In order to describe the possibility of hybrid star configurations we adopt the cooling of the quark core following the lines of [34]. There the quark core cooling is described by adopting a small but nonvanishing density dependent pairing gap (X-gap) for those quarks with the otherwise in the 2SC phase unpaired colour.

# 4 Results

For the purely hadronic scenario the resulting cooling curves are shown in Fig. 2. As expected, the stiffer DD2 hadronic EoS leads to a flatter density profile and therefore to weaker cooling activity when compared to the relatively soft HHJ and HDD EoS, provided the same effective pion gap $\widetilde{\omega}(n)$ is used. Consequently a rather large CS mass range is required in order to cover the full set of cooling data. It is a remarkable and nontrivial fact that the description of all cooling data after this change of the EoS is possible without changing any of the formerly adjusted cooling inputs! Note that the mass $M = 2.426\ M_\odot$ fitted for the CasA cooling data is in the range given by the original analysis of Ho and Heinke [3]. The fit of the slope, as indicated in the inset of the figure, requires the choice of the thermal conductivity suppression pre-factor $\zeta_\kappa = 0.021$. The cooling of the hot source XMMU-J1732 is explained by a neutron star with the mass $1.29\ M_\odot$ being again larger than the ($\simeq 1\ M_\odot$) which was required with the HHJ and HDD EoS.

Turning our attention to the scenario of a hybrid EoS, we observe that the presence of a quark core leads to an acceleration of the cooling. The full set of cooling data can again be described (see Fig. 3) but this time by varying the star masses within a range much narrower than for the stiff, purely hadronic DD2 sequence. The cooling data for CasA are now explained with quark core hybrid star of $M = 1.674\ M_\odot$. An appropriate slop of the

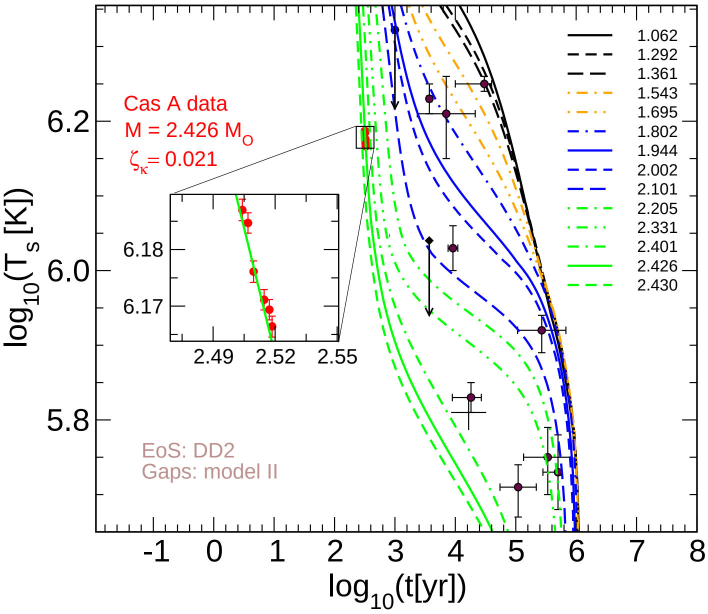


Figure 2: Cooling curves for a neutron star sequence according to the stiff hadronic DD2 EoS; $T_s$ is the surface temperature, $t$ is the CS age. The color coding corresponds to different mass ranges: $M = 1.0 - 1.5\ M_\odot$ (black), $M = 1.5 - 1.8\ M_\odot$ (orange), $M = 1.8 - 2.2\ M_\odot$ (blue) and $M = 2.2 - 2.5\ M_\odot$ (green). Cooling data for CasA are explained with a heavy neutron star of $M = 2.426\ M_\odot$. To recover an appropriate slope of the curve requires a pre-factor $\zeta_\kappa = 0.021$.

curve requires the same pre-factor $\zeta_\kappa = 0.021$, as has been used in the purely hadronic scenario, see Fig. 2.

# 5 Concluding remarks

We have demonstrated that the presently known cooling data on Cassiopeia A and the hot source XMMU-J1732, as well as other cooling data, can be appropriately described within our nuclear medium cooling scenario, under the assumption that different sources have different masses, either by purely hadronic or by hybrid star configurations. Large values of the compact star

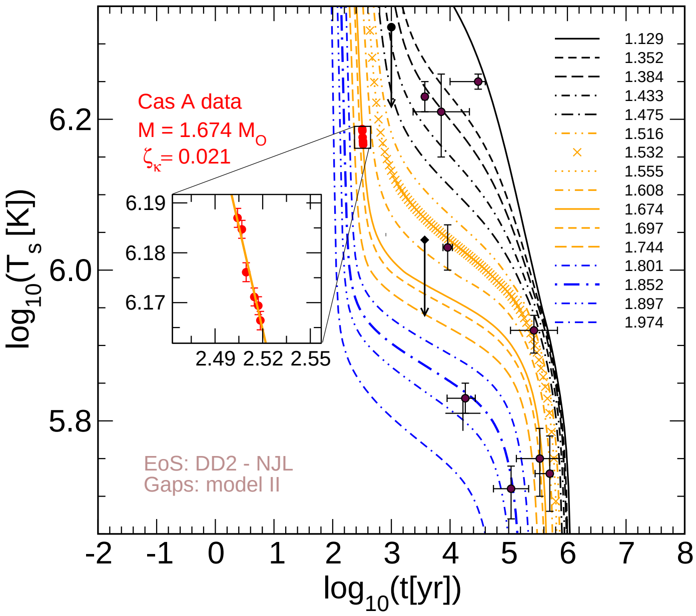


Figure 3: Cooling curves for a CS sequence according to the DD2 - NJL hybrid EoS. The color coding is as in Fig. 2. Cooling data for CasA are explained with a quark core hybrid star of $M = 1.674\ M_\odot$. To recover an appropriate slope of the curve requires a pre-factor $\zeta_\kappa = 0.021$.

radii and the maximum mass, as it might be motivated by observations, are compatible with our nuclear medium cooling scenario provided one uses a stiff EoS. Here we demonstrated it with the DD2 EoS. For computing the cooling curves we exploited the very same parameter set of the purely hadronic model as in [16]. If we allowed for a decrease of the effective pion gap with increasing density we could diminish the resulting values of the mass of the neutron star in Cassiopeia A. This will be demonstrated elsewhere.

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